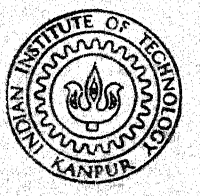
DETERMINATION OF VOID FRACTION IN TWO-PHASE AIR-WATER FLOW BY GAMMA RAY ATTENUATION METHOD

BY

M. SIVA KUMAR



DEPARTMENT OF MECHANICAL ENGINEERING

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DETERMINATION OF VOID FRACTION IN TWO-PHASE AIR-WATER FLOW BY GAMMA RAY ATTENUATION METHOD

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for the Degree of

MASTER OF TECHNOLOGY

by

M. SIVA KUMAR

to the
Department of Mechanical Engineering
INDIAN INSTITUTE OF TECHNOLOGY, KANPUR
October, 1968

DEDICATED TO MY PARENTS

CERTIFICATE

This is to certify that this work has been carried out under my supervision and has not been submitted elsewhere for a degree.

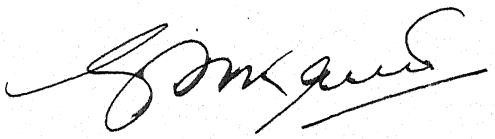

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TABLE OF CONTENTS

CHAPTERS		Page
I	Introduction	1
II	Void Fraction Determination: Theory	3
III	Previous Related Work	11
IV	Experimental Set-up	16
V	Experimental Procedure	22
VI	Results and Discussion	30
	References	33
	Appendix	
	Counting Statistics and Error Analysis	35

LIST OF FIGURES

		Page
1.	Flow diagram of the experimental set-up	15
2.	Block diagram of the Gamma ray apparatus	17
3.	Sectional view of the source, collimator, detector assembly	18
4.	Variation of void fraction with air weight fraction	25
5.	Variation of void fraction with pressure	26
6.	Variation of slip ratio with air weight fraction	27
7.	Variation of slip ratio with pressure	28
8.	Void distribution across the width of the channel	29

NOMENCLATURE

Symbol

A_g	Cross sectional area of channel occupied by gas.
A_f	Cross sectional area of channel occupied by liquid.
AWF	Air Weight Fraction - fractional weight of air in the air-water mixture
$\dot{m}_t$	Mass flow rate of the mixture
N	Intensity of the Gamma ray beam
N_o	Initial intensity
N_l	Intensity after passing through the channel filled with liquid
N_g	Intensity after passing through the channel filled with gas
N_m	Intensity after passing through channel filled with mixture
P(n)	Probability of observing exactly n counts in a given time
r	Counting rate
r_b	Background counting rate
S	Slip ratio
v_f	Specific volume of liquid
v_g	Specific volume of vapour
V_f	Velocity of liquid
V_g	Velocity of vapour
x'	Quality of the mixture
x	Breadth of the channel

Symbol

x_g	Length of Ga—a ray path through the gas
x_l	Length of Ga—a ray path through the liquid
x_s	Total thickness of the channel walls
	Void fraction
μ	Linear absorption coefficient
μ_g	Linear absorption coefficient for gas
μ_l	Linear absorption coefficient for liquid
μ_s	Linear absorption coefficient for channel wall material
σ	Standard deviation

ABSTRACT

M. Siva Kumar, M. Tech., Indian Institute of Technology, Kanpur, "Determination of Void Fraction in Two-phase Air-water flow by Gamma Ray Attenuation Method."

The variation of void fraction and slip ratio with pressure and air weight fraction in vertical two-phase air-water flow is investigated. Void fraction is measured using Gamma ray attenuation method, and from this the slip ratio is calculated. The theory of Gamma ray attenuation technique, and the experimental procedure for void fraction determination are described in detail. A review of the literature is given. A brief discussion on counting statistics and error analysis is also included.

An aluminium pipe of square cross section (3.33 cm □ internal) is used as the test channel. The parameter ranges studied are pressure 3.0 psig to 1?.5 psig, and air weight fraction 0 to 3.6%. Curves showing the effect of pressure and air weight fraction on void fraction and slip ratio are presented. Void fraction is found to increase with pressure due to the sharp reduction in slip ratio when the pressure is increased. Increase in air weight fraction also decreases slip ratio. The distribution of voids within the cross section of th flow channel, indicating a definite tendency for the voids to collect near the centre, is also shown.

CHAPTER I

INTRODUCTION

The advent of Boiling Water Nuclear Reactors provided the principal stimulation for void fraction investigations. The main objective of such studies has been to obtain void data for use in the analysis of two-phase flow and boiling heat transfer, and for computing moderator densities in nuclear reactors.

Void fraction may be defined as the fraction of cross sectional flow area occupied by the gas in a two-phase gas-liquid flow. There is a large difference in the Gamma ray absorption coefficients of the two phases. The Gamma ray attenuation method of void fraction determination makes use of this fact.

Boiling heat transfer is a very complex phenomenon. In this case we have to take into consideration the surface characteristics, the surface tension, the latent heat of evaporation, the pressure, the density and possibly other properties of the vapour in addition to the variables involved in liquid phase convection-the viscosity, the density, the thermal conductivity and specific heat of the liquid, the geometry of the system etc.

In the case of Boiling Water Nuclear Reactors where the boiling water also serves as a moderator, void fraction affects the coolant density, core neutron kinetics and reactor stability. The steam voids displace a part of the coolant and the coolant density is reduced. The change in reactivity with void fraction is known as the void coefficient of reactivity. A negative void

coefficient has a stabilizing effect on reactor operation. An increase in steam production due to an accidental increase in reactivity tends to reduce the reactivity resulting in the lowering of the power level of the reactor.

Due to the complexity of the two-phase flow and boiling heat transfer, there is at present no satisfactory theory which can predict the void fraction for all conditions. An additional complication in this problem is that the two phases move with different velocities. (The ratio of the vapour velocity to the liquid velocity is known as Slip Ratio). Therefore, the approach has always been empirical and considerable work has been done on experimental measurement of void fraction. Experimental values of void fraction at pressures ranging from 150 psig to 1000 psig are available in the literature.[5,6]

The most important parameters that affect the void fraction and the slip ratio are the pressure and the mixture quality. The heat transfer rate, the flow channel geometry and the superficial liquid velocity have also been found to affect the void fraction and slip ratio to a lesser degree.

The aim of the present investigation is to study the variation of void fraction and slip ratio in two-phase air-water flow with air weight fraction and pressure at low pressures (3 to 12.6 psig).

CHAPTER II

VOID FRACTION DETERMINATION: THEORY

SECTION 1

Quality and Void Fraction in a Nonflow System:

The quality 'x' of a mixture of vapour and liquid in a nonflow system or where these is no relative motion between the gas and the liquid phase is defined as

$$x' = \frac{\text{Mass of the vapour in the mixture}}{\text{Total mass of the mixture}}$$

The void fraction or void volume fraction 'α' is defined as

$$\alpha = \frac{\text{Volume of vapour in the mixture}}{\text{Total volume of the mixture}}$$

The relationship between the quality and the void fraction may be obtained by considering a certain volume containing unit mass of the mixture in thermal equilibrium.

The quality of the mixture is x'

The volume of vapour = $x'v_g$

The volume of liquid = $(1-x')\,v_f$

where

v_g is the specific volume of vapour and

v_f is the specific volume of liquid.

$$\text{Void fraction } (\alpha) = \frac{\text{Volume of vapour}}{\text{Volume of vapour + Volume of liquid}}$$

$$= \frac{x' v_g}{x' v_g + (1-x) v_f}$$

$$\text{i.e.} \quad \alpha = \frac{1}{1 + \left(\frac{1-x'}{x'}\right) \frac{v_f}{v_g}} \qquad (2.1)$$

Expression for Void Fraction in a Flow System:

In deriving the expression for void fraction in a nonflow system it was assumed that there was no relative motion between the liquid and the vapour. In the case of moving two-phase mixtures the vapour, because of buoyancy, tends to slip past the liquid. The vapour velocity is more than the liquid velocity, and the ratio of the vapour velocity to the liquid velocity is called slip ratio 'S'.

The quality at any cross section of the flow channel is defined as

$$x' = \frac{\text{Mass flow rate of vapour}}{\text{Mass flow rate of mixture}}$$

If the total mass flow rate of the mixture is $\dot{m}_t$ and the quality at the particular cross section is x', the velocities of vapour (V_g) and liquid (V_f) are given by

$$V_g = \frac{v_g \dot{m}_t x'}{A_g} \qquad .. \qquad .. \qquad (2.2)$$

$$V_f = \frac{v_f \dot{m}_t (1-x')}{A_f} \qquad .. \qquad .. \qquad (2.3)$$

Where A_g and A_f are the cross sectional areas of the gas phase and the liquid phase perpendicular to the flow direction.

From (2.2) and (2.3)

$$\text{Slip ratio (S)} = \frac{V_g}{V_f} = \frac{x' A_f v_g}{(1-x') A_g v_f} \qquad (2.4)$$

Considering only a small length of the channel (the changes in the properties of the mixture are negligibly small) the ratio of the vapour phase volume to the total volume is the same as the ratio of the cross sectional area occupied by the vapour (A_g) to the total cross sectional area of the channel.

i.e. $$\alpha = \frac{A_g}{A_g + A_f} \quad \ldots \qquad (2.5)$$

$$\frac{A_f}{A_g} = \frac{1-\alpha}{\alpha} \quad \ldots \qquad (2.6)$$

Substituting the expression for $\frac{A_f}{A_g}$ in Equation (2.4)

$$S = \frac{x'}{1-x'} \frac{1-\alpha}{\alpha} \frac{v_g}{v_f} \quad \ldots \qquad (2.7)$$

The above expression can be rearranged to give an expression for α in terms of quality and slip ratio[1]

$$\alpha = \frac{1}{1 + \left(\frac{1-x'}{x'}\right)\left(\frac{v_f}{v_g}\right) S} \quad \ldots \qquad (2.8)$$

It may be noted that the relationship between void

fraction and quality for no slip (S = 1) is the same as for the nonflow system.

The effect of slip is to reduce the value of α corresponding to a particular value of x'. A high slip ratio is an advantage from both the heat transfer and the moderating effect stand points.

SECTION 2

Gamma Ray Attenuation Method:

In the past few years investigators have employed different techniques for experimental void measurement. They include use of radioactive tracers, X-ray attenuation, Beta ray attenuation and Gamma ray attenuation. Among these the Gamma ray attenuation is the most widely applied and evaluated technique.

As Gamma rays pass through matter the photons are absorbed and the intensity decreases exponentially with the distance. The extent of absorption is proportional to the intensity of radiation and to the thickness of the medium at a given point.

$$dN = -\mu N \, dx \qquad .. \qquad .. \qquad (2.9)$$

where

N is the intensity of radiation

μ is the linear absorption coefficient and

dx is the thickness of the material.

This can be integrated to give the attenuation of the Gamma ray beam for a finite thickness x

$$\frac{N}{N_o} = e^{-\mu x} \qquad .. \qquad .. \qquad (2.10)$$

where

N_o is the initial intensity,

and N is the final intensity.

The principal assumptions are:

1. The radiation is monoenergetic.
2. The Gamma ray beam consists of parallel rays and is very thin.
3. The two-phase mixture can be represented in layers of gas and liquid perpendicular to the incident radiation.

The Gamma ray attenuation method of void fraction measurement is based on the fact that the linear absorption coefficient (μ) is different for the two phase constituting the two - phase flow. This is mainly due to the large difference in density. In measuring void fraction of a two - phase mixture flowing in a channel, the radiation from the Gamma ray source passes though the flow channel and the attenuated radiation reaches the detector.

If the radiation passes through the channel when completely filled with gas the attenuation is

$$\frac{N_g}{N_o} = e^{-\mu_g x} \; e^{-\mu_s x_s} \qquad .. \qquad .. \qquad (2.11)$$

where

μ_g is the linear absorption coefficient of gas,

μ_s is the linear absorption coefficient of the channel wall material,

x_s is the total thickness of channel walls, and

x is the breadth of the channel.

A similar measurement at the same position with the channel completely filled with liquid gives

$$\frac{N_l}{N_o} = e^{-\mu_l x} \; e^{-\mu_s x_s} \qquad .. \qquad .. \qquad (2.12)$$

where μ_l is the linear absorption coefficient of the liquid.

Finally the measurement obtained with the channel filled partially with gas and partially with vapour i.e. filled with the two - phase mixture is given by

$$\frac{N_m}{N_o} = e^{-\mu_l x_l} \; e^{-\mu_g x_g} \; e^{-\mu_s x_s} \qquad .. \qquad (2.13)$$

From the three equations (2.11), (2.12) and (2.13), it is possible to derive an expression for the local void fraction $(\frac{x_g}{x})$ i.e. the fraction of the path of the Gamma ray beam through the gaseous phase in the flow channel.[2,7]

$$\frac{x_g}{x} = \alpha = \frac{\ln \left(\frac{N_m}{N_l} \right)}{\ln \left(\frac{N_g}{N_l} \right)} \qquad .. \qquad .. \qquad (2.14)$$

Thus it is possible to determine the local void fraction by making three radiation measurements. It may be noted that the linear absorption coefficients are not present in the expression for void fraction, and so it is not necessary to determine them.

In order to determine the mean or overall void fraction for the whole cross section, a series of count rate measurements at different positions along the width of the channel is made and the results are numerically integrated along the width.

One of the assumption made in deriving the expression for α is that the Gamma ray beam is very thin. It can be shown that if this assumption is discarded it is no longer possible to derive a simple expression for the void fraction.

CHAPTER III

PREVIOUS RELATED WORK

Hooker and Popper[2] have given a detailed description of the Gamma ray attenuation method. They used Thulium-170 as the Gamma ray source. The test section was a vertical stainless steel channel of rectangular cross section. They made several lucite mock-up measurements and verified the following:

1. For all practical purposes a truly exponential attenuation can be assumed with layers of vapour and liquid perpendicular to the path of radiation.

2. Homogeneous bubbles in water can be represented by alternate layers of vapour and liquid arranged perpendicular to the incident radiation.

After making a detailed error analysis they concluded that the uncertainty (for their conditions) at full void range was 2.9%. There was a serious loss of accuracy in void fractions below 0.100. With uniform distribution of bubbles in the region between 0.100 and 1.00 the maximum probable error occurred with the void fraction of 0.100 and was ± 7.5%.

Their measurements on mock-ups of preferential distributions which occur when voids are concentrated at particular locations indicated that the method was quite inaccurate for

such measurements. They have pointed out that the error in measuring preferential void distributions could be reduced by viewing only a fraction of the width of the flow channel at any instant. Then the region examined would have more nearly uniform distribution of bubbles. Such measurements could be made at various points along the width of the channel and an average void fraction computed. Subsequent investigators employed this method in preference to Hooker and Popper's 'one-shot' method i.e. viewing the whole width of the channel at the same time.

The other factors affecting the accuracy of the measurements were the loss of strength of the Gamma ray source over the period during which the tests were made and errors due to radiation reaching the detector by parallel paths external to the mixture.

Petrick and Swanson[3] used a traversing method in which the platform carrying the source and the detector was traversed along the width of the channel to obtain a series of void measurements. From these measurements the distribution of voids along the width of the channel was obtained and this was integrated to give a mean void fraction for the cross section. They also determined the accuracy of the method using lucite mock-ups. They found that the average difference between the void fraction measured by the Gamma ray attenuation method and the known void fraction for several simulated void distributions was 7.3% of the known void fraction when the traverse technique

was used. The difference with 'one-shot' method was 36.5%. However, for the mock-ups which very nearly resembled the homogeneous distribution of voids the difference between the actual and measured void fraction was similar, about 1.5%.

Isbin, Sher and Eddy[4] measured void fractions and pressure drops for steam-water flows in a 2.2 cm (internal diameter) vertical tube at atmospheric pressure over a quality range of 0 to 4%. Selenium - 75 was used as the Gamma ray source and the diameter of the collimated beam was 1.5 mm. The carriage on which the source detector assembly was mounted could be rotated around the test section and could be moved from one side of the channel to the other, thus traversing all chord positions.

Isbin, Rodriguez, Larson and Pattie[5] measured the void fraction using Gamma ray attenuation method for steam-water flows in an adiabatic horizontal test section of 0.434 in. inner diameter at pressures varying from 400 to 1000 psig. Experimental values of void fraction at 400, 600, 800 and 1000 psig along with that predicted by Martinelli are given. The paper does not discuss the accuracy of the method.

Marchaterre and Petrick[6] have presented working curves for the prediction of the velocity or slip ratio (steam velocity/water velocity) at 150, 250, 400 and 600 psig. The slip ratio was calculated from steam void fraction which was measured using Gamma ray attenuation method. The pressure was varied from 150 to 200 psig, quality from 0 to 25% and the

channel equivalent diameter from 0.4 to 2 inches.

Marchaterre and Petrick concluded that the slip ratio was affected by pressure, mixture quality, superficial liquid velocity and to a lesser degree by channel geometry.

Condon and Cher[7] conducted a study to establish the suitability of Gamma ray attenuation method for measuring void fractions in a parallel rod array. The error, determined by taking measurements with lucite mock-ups was found to vary from 7 to 13%. They conducted several tests with air-water mixtures and employed the traverse technique. They observed a definite tendency for the gas to collect near the centre of the test section.

Perkins and Yusuf[3] developed a Beta ray attenuation void measurement technique for local boiling. After analysing the literature concerning the Gamma ray attenuation method they conclude that the Gamma ray attenuation method is reasonably accurate for the determination of void volumes when the voids are distributed in a homogeneous manner and the test section offers a radiation path greater than about 2500 mg/cm^2 (equivalent of one inch of water).

The literature survey indicates that the Gamma ray attenuation is the most widely used method for void fraction measurement and that is considered the most suitable method except in the case of very small void fractions. The accuracy of the method largely depends on the statistical error in the count rate measurements. The error reduces as the count rate increases, and this can be achieved by using a stronger γ-ray source.

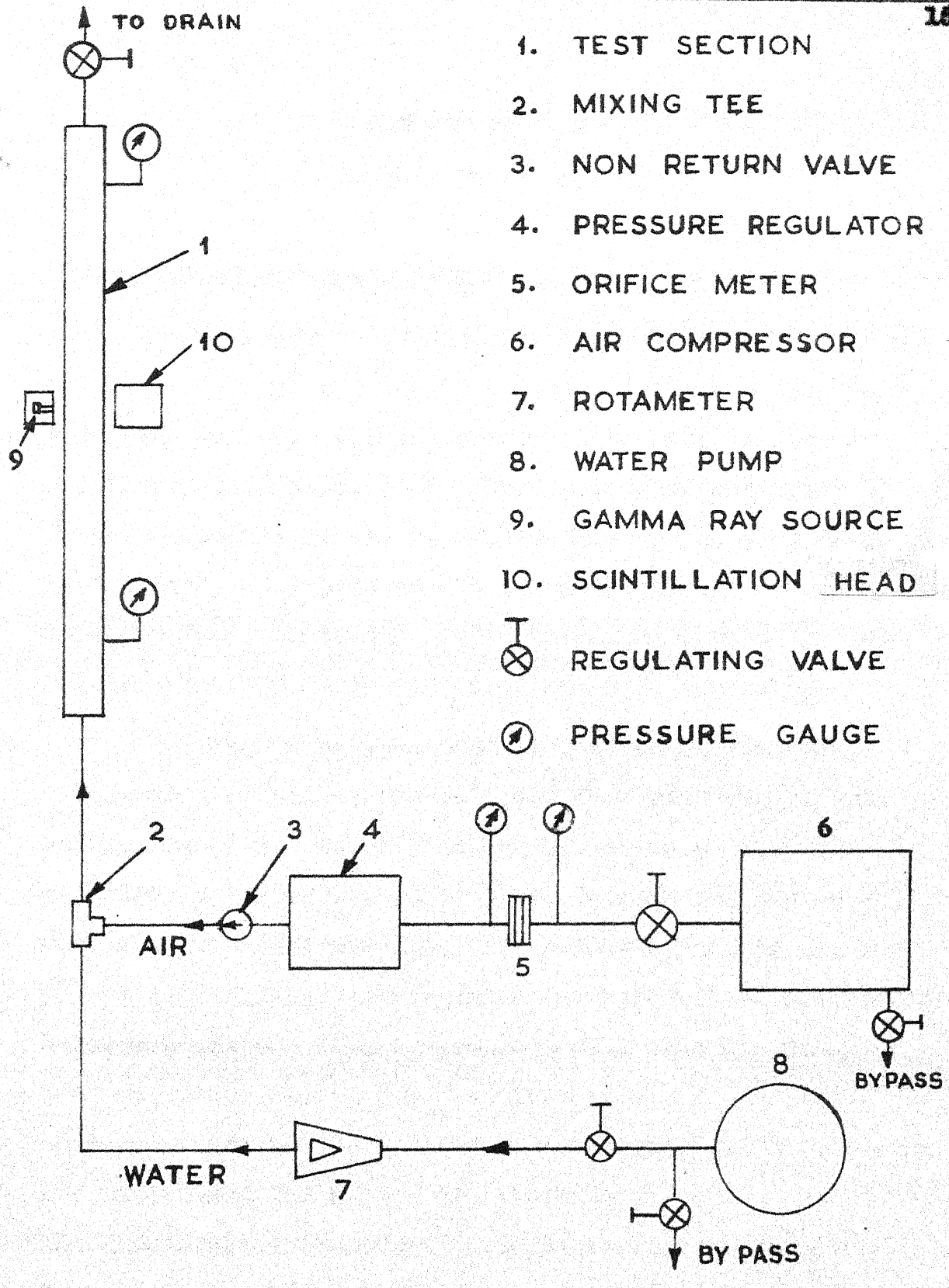


FIGURE 1 FLOW DIAGRAM OF THE EXPERIMENTAL SETUP

CHAPTER IV

EXPERIMENTAL SET-UP

Generation of Two-phase Flow:

A flow diagram of the experimental set-up is shown in Figure 1. The air supply is obtained from a two-stage, reciprocating type air compressor. The rate of flow of air is measured using an orifice meter fabricated and fitted according to the specifications of the ASME Power Test Codes[9]. Air pressure is regulated by a diaphragm type pressure regulator. Water is supplied by a pump and a rotameter is used to measure the water flow rate.

Air and water are mixed in a standard pipe tee. This method of mixing was selected from previous investigations involving the generation of air-water mixtures reported by Martinelli et al[10] and Johnson and Abou-Sabe[11]. To quote from Reference 10, "The method of mixing the two phases (air and water) was chosen as a result of considerable experimentation. Trials were made with both air injected into water and liquid injected into air. The different modes of injection were tried to minimize slugging which is the name given for stream of alternate plugs of liquid and air. Such plugs were from a few inches to several feet long depending upon the rates of flow. The arrangement necessary for minimum slugging required the introduction of air into

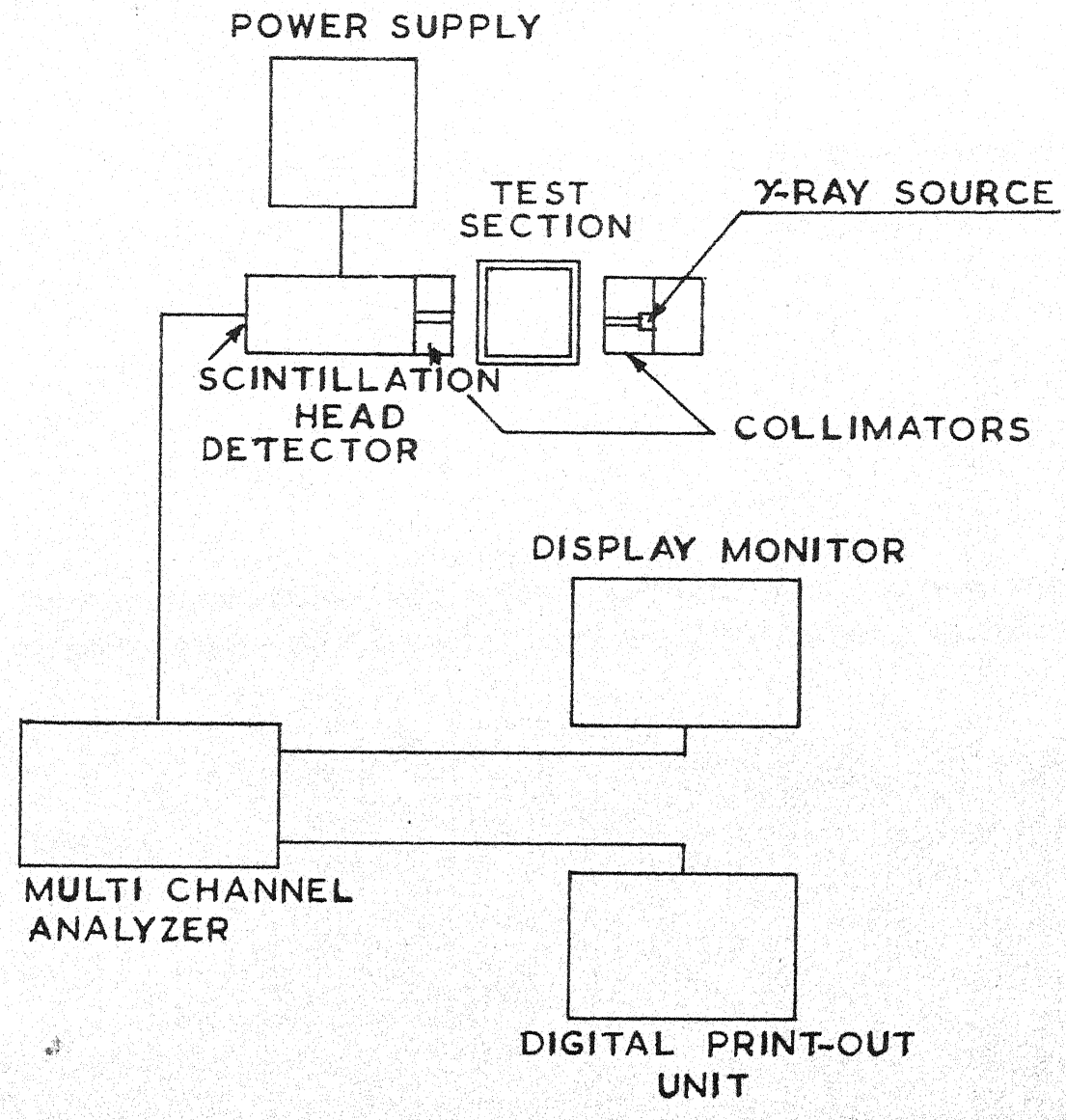
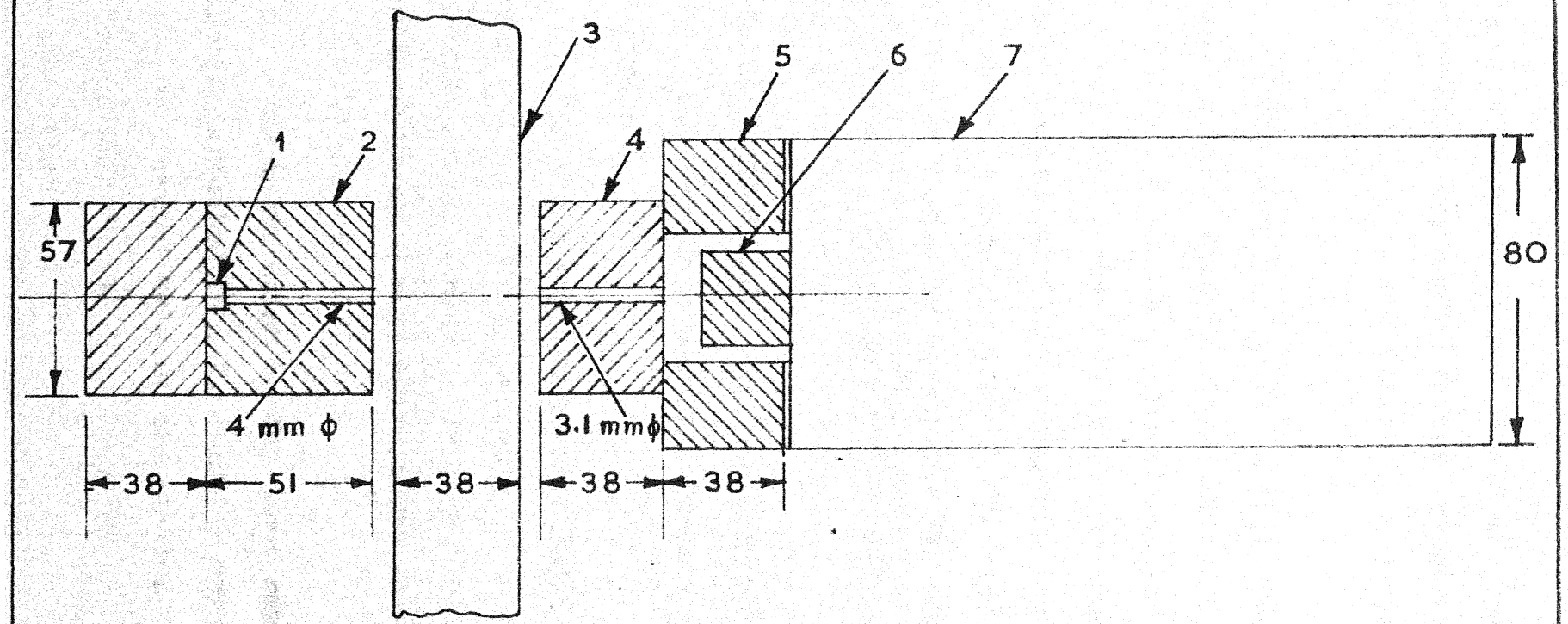


FIGURE 2 BLOCK DIAGRAM OF THE GAMMA RAY APPARATUS



1. Y-RAY SOURCE 2. COLLIMATOR 3. TEST SECTION 4. COLLIMATOR 5. LEAD SHIELDING FOR SCINTILLATION CRYSTAL 6. SCINTILLATION CRYSTAL 7. PHOTOMULTIPLIER ASSEMBLY.

FIGURE 3 SECTIONAL VIEW OF THE SOURCE, COLLIMATOR, DETECTOR ASSEMBLY.

ALL DIMENSIONS IN mm.

the upper surface of the liquid and perpendicular to it. Furthermore any bends, valves or other obstructions between the injection point and the measuring section must be avoided."

The test section is an aluminium pipe of square cross-section, (3.33 cm internal and 3.81 cm external) and it is 152 cm long. The air-water mixture enters the vertical test section at the bottom and flows upward. After leaving the test section at the top, the mixture is exhausted into the drain. The flow rate of water and air can be varied by regulating the valves at the outlet of the circulating pump and the valve at the outlet of the air-compressor.

Gamma Ray Apparatus

A block diagram of the Gamma ray apparatus is shown in Figure 2.

The Gamma ray source is a Thulium-170 pellet, 3 mm diameter and 3 mm height, enclosed in an aluminium capsule. The strength of the source on July 30, 1968, was 0.575 Curie. Thulium-170 has a half life of 127 days and two energy peaks at 0.053 Mev and 0.084 Mev.

The collimation of the Gamma ray beam at the source side is effected by a lead collimator of 5.0 cm length with a 4.0 mm diameter hole at the centre. Collimation at the detector side is obtained by a 3.8 cm thick lead block with a 3.1 mm aperture.

The detector is a Trombay Electronic Instrumentation Scintillation Head (Type SH 635). The head consists of a combination of a scintillation crystal, a photomultiplier and a cathode ray follower in one cylindrical housing, and acts as a transducer converting Gamma radiation into electrical pulses.

The scintillation crystal is Thallium activated. Sodium Iodine, 3.2 cm diameter and 2.5 cm thick, hermetically sealed with a circular glass top. The transparent side of the crystal is in optical contact with the photomultiplier. The assembly is connected to a cathode follower type preamplifier. In order to isolate the scintillation crystal from extraneous radiation and to ensure that only the Gamma rays which pass through the test section reach the crystal it is surrounded by a thick lead shield.

Referring to the block diagram given in Figure 2, and the detailed sectional view of the Gamma ray source, collimator, detector assembly shown in Figure 3, the collimated Gamma ray beam from the source passes through the test section and reaches the detector. The Gamma radiation falling on the crystal produces 'sintillations' or light emissions which fall on the photocathode of the photomultiplier. Photoelectrons are emitted from the cathode and they move towards the dynodes to which successively higher potentials are applied. Each electron striking a dynode produces more electrons by secondary emission. This process is repeated and the electron

current is amplified as the electrons are accelerated from dynode to dynode. The large number of electrons from the last cathode is collected by the anode resulting in an electrical pulse, which is rendered available at the output, through a cathode follower. Each incident Gamma ray produces a voltage pulse and its magnitude is proportional to the energy of the Gamma ray.

The voltage pulses from the scintillation head are fed into a Nuclear Data - 110 Multichannel Analyzer with 128 channels for amplitude analysis. The amplitude analysis of the voltage pulses gives the energy distribution or spectrum of Gamma rays. It is also referred to as pulse-height analysis. The incoming signals are analyzed by the multichannel analyzer and the resulting data is stored in its magnetic core memory. Data stored in the memory can be observed in the analog form, either during or after accumulation, on the cathode ray screen of Nuclear Data-410 Display Monitor. An IBM Selectric Typewriter fitted with a Nuclear Data - 316 Autofinger provides the digital print out of the data.

The assembly consisting of the source collimators and the detector is mounted on a horizontal platform. In order to get precise and reproducible positioning of the source and the detector, the platform is fixed to a traversing mechanism with a vertical traverse of 48 cm and a horizontal traverse of 15 cm.

CHAPTER V

EXPERIMENTAL PROCEDURE

The flow rates of air and water were adjusted to the desired values using the regulating and bypass valves at the outlets of the air compressor and the water pump. Great care was taken to see that these flow rates remained constant throughout the test run. The pressure of the flowing air-water mixture in the test section was adjusted by altering the setting of the air pressure regulator.

The platform carrying the source, collimator, detector assembly was moved across the width of the test section by operating the traverse mechanism. Three count rate measurements (with air, water and the mixture in the test section) to determine the local void fraction were taken at 12 locations. These 12 locations were equally distributed across the width of the flow channel and were 2.5 mm apart.

The multichannel analyzer was caliberated with a Cs^{137} (0.662 Mev peak) standard source. The zero level adjustment was made using a pulse generator and the linearity of the analyzer was checked with a Co^{57} (1.17 Mev peak) standard source.

A counting period of one live minute was used for each count rate measurement. Thulium-170 has a peak at 0.084 Mev.

One of the important assumptions made in deriving the expression for void fraction is that the Gamma ray beam is monoenergetic. In order to satisfy this assumption only Gamma rays in the energy range of 0.067 Mev to 0.101 Mev were taken into consideration. The number of counts varied from 83,000 to 40,000. The corresponding statistical errors varied from 0.35% to 0.5% (Standard error) and 0.2% to 0.34% (Probable error). (A discussion on counting statistics and error analysis is given in the Appendix.)

The experiments were conducted on a schedule such that no correction for the decay of the Gamma ray source was required.

A possible source of error in the count rate measurements is the variation in the gain of the photo-multiplier tube with variations in the high voltage supply. The photo-multiplier tube gain changes with the seventh power of the voltage (E_h) supplied to it. For small variations in E_h the error is seven times the regulation of E_h. This error was minimised in the following manner. The high voltage supply to the photomultiplier was from the Trombay Electronic Instrumentation High Voltage Unit HV 200. This unit is specifically designed to provide stable voltage with excellent regulation. (The output voltage variation is less than 0.001% for 1.0% change in the line voltage.) Further, the supply to the High Voltage Unit itself was through a voltage stabilizer.

The calculation of local void fraction from the count rates and their numerical integration to determine the overall

void fraction for the entire cross section was done on an IBM 7044 Computer. Knowing the void fraction, slip ratio was calculated using the Equation 2.7.

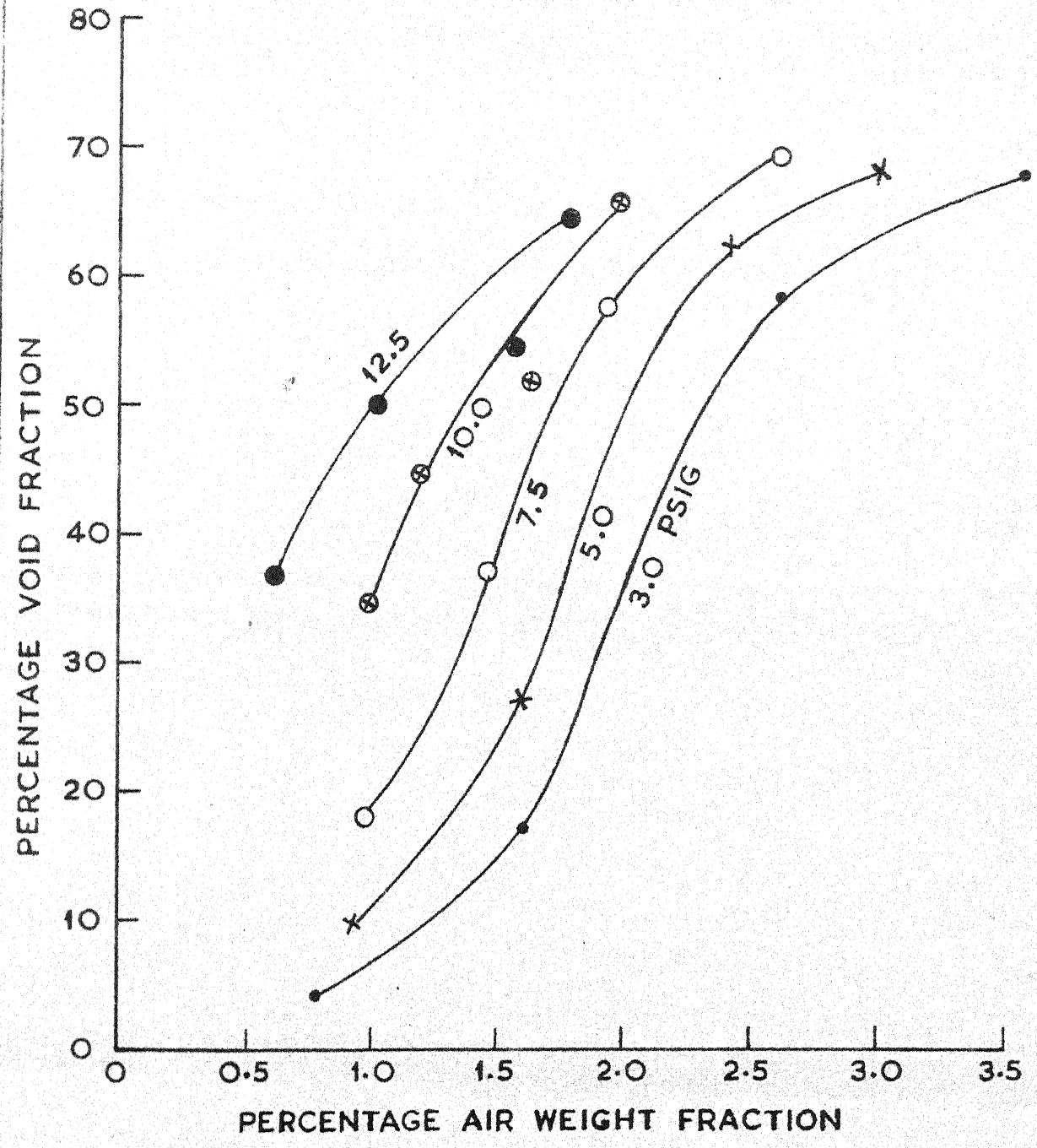


FIGURE 4 VARIATION OF VOID FRACTION WITH AIR WEIGHT FRACTION

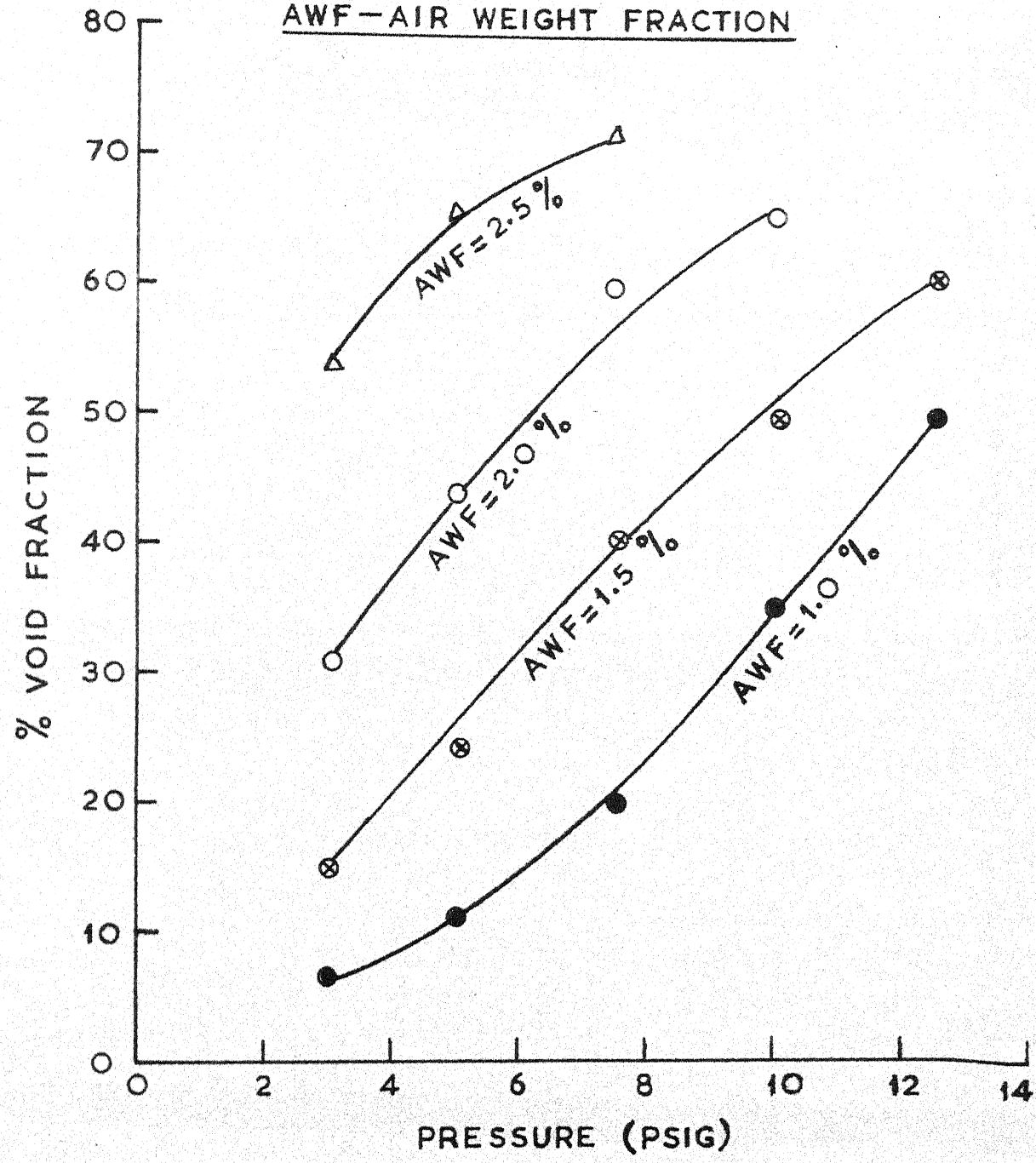


FIGURE 5 VARIATION OF VOID FRACTION WITH PRESSURE

* These points were obtained by cross plotting from Figure 4.

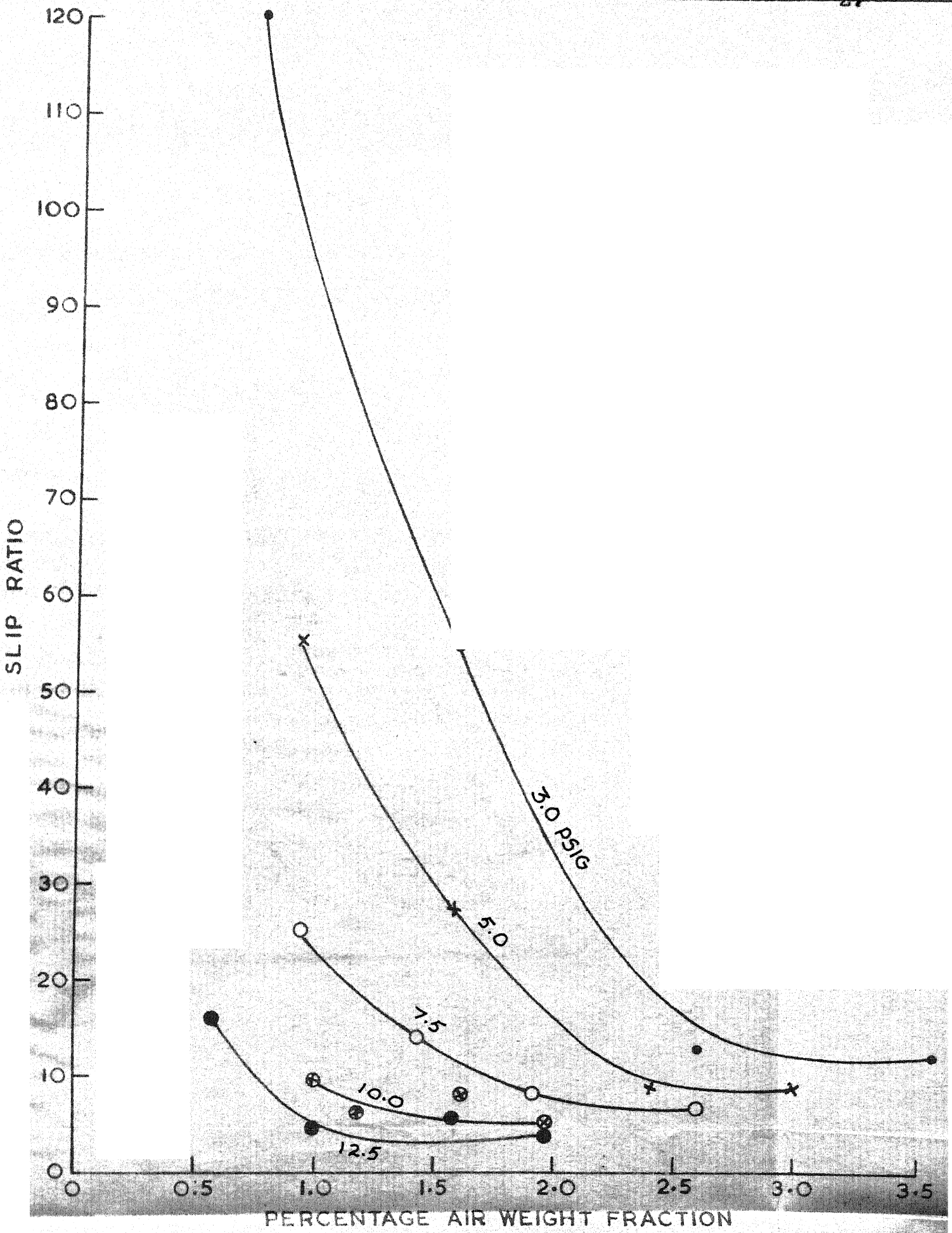


FIGURE 6. VARIATION OF SLIP RATIO WITH AIR WEIGHT FRACTION

* These points were obtained by calculation from measured void fraction

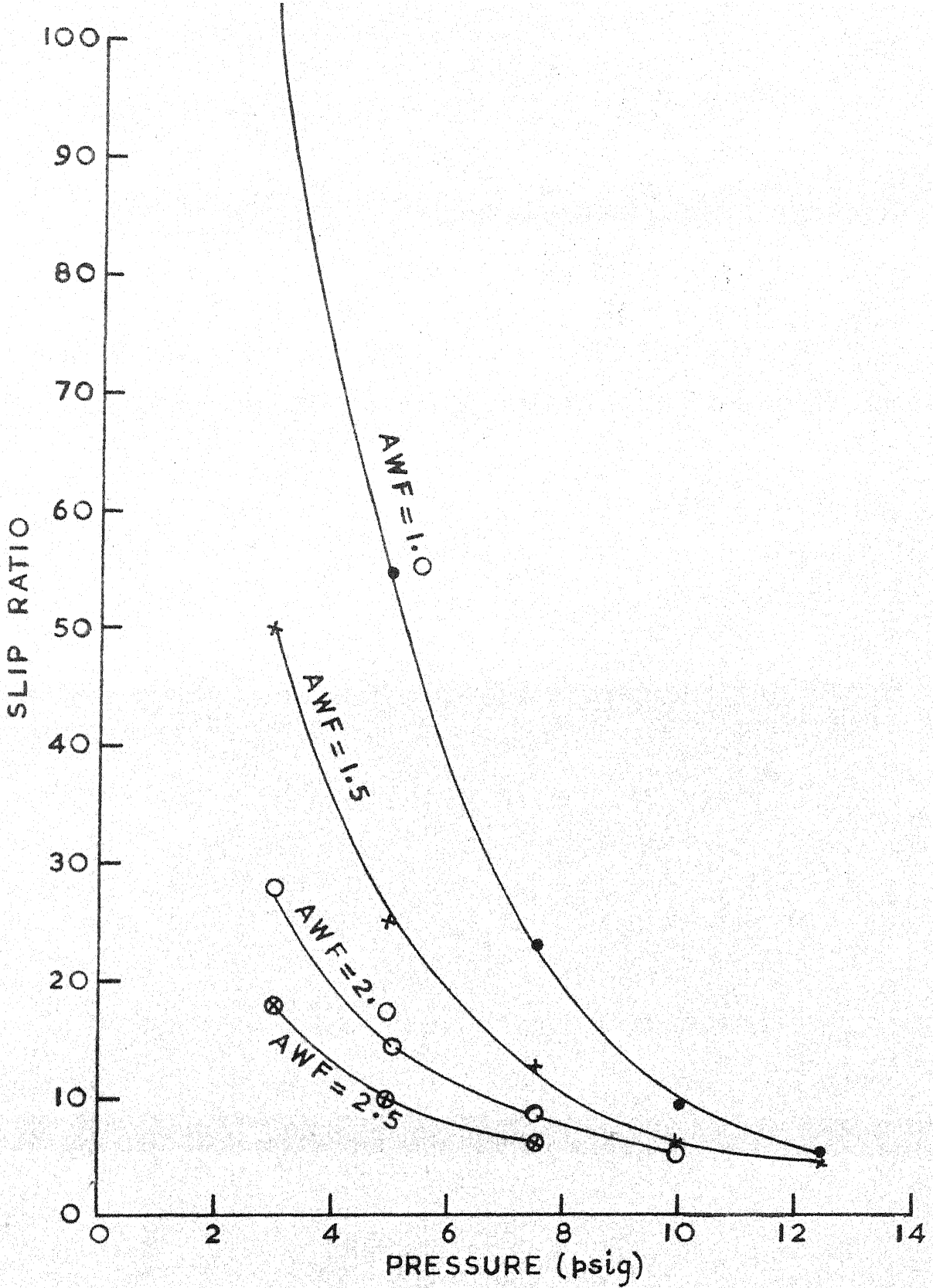


FIGURE 7 VARIATION OF SLIP RATIO WITH PRESSURE

• These points were obtained by cross plotting from Figure 6.

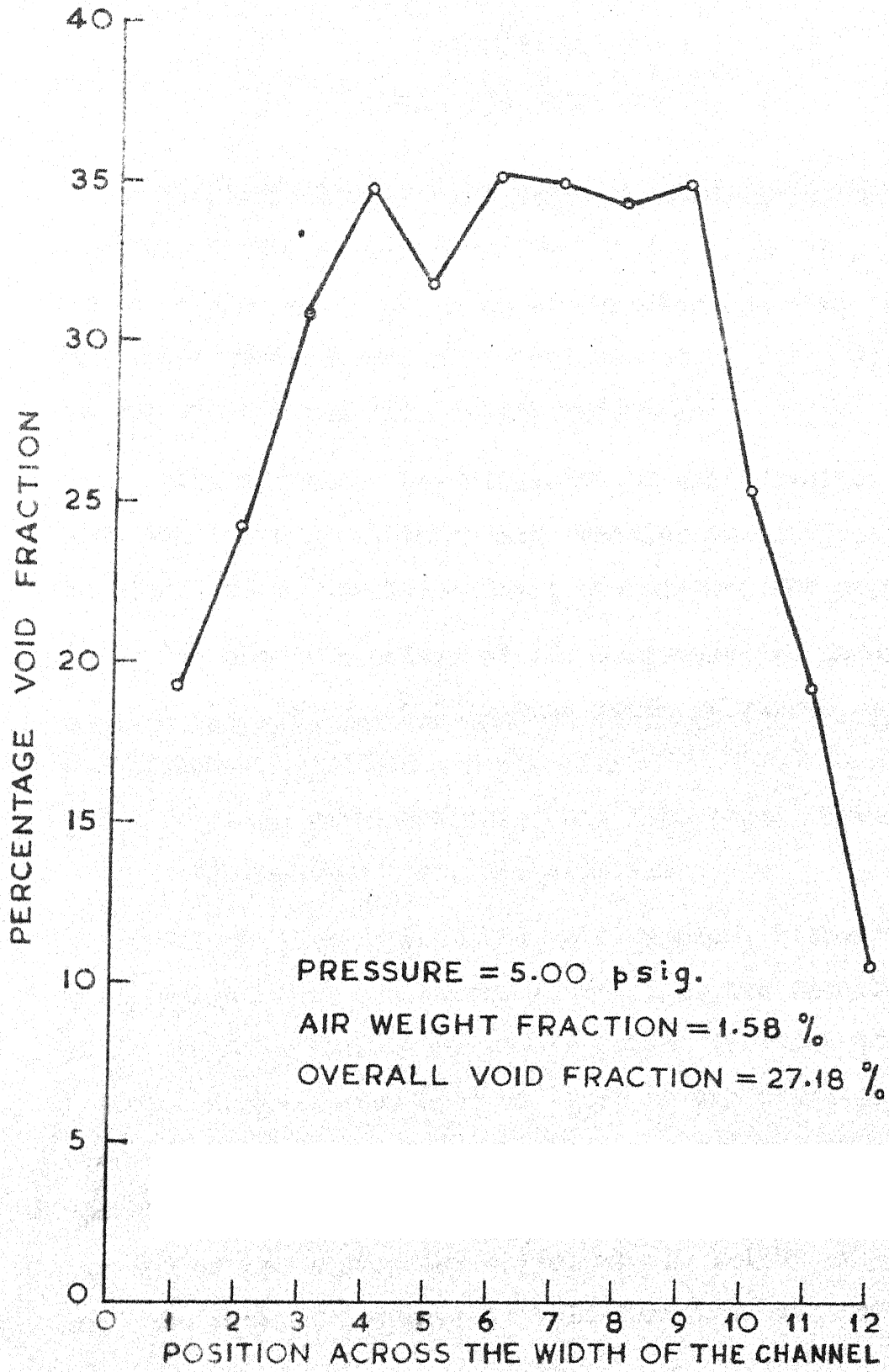


FIGURE 8. VOID DISTRIBUTION ACROSS THE WIDTH OF THE CHANNEL

CHAPTER VI

RESULTS AND DISCUSSION

The variation of void fraction with air weight fraction for five different pressures from 3.0 psig to 12.5 psig is given in Figure 4. As is to be expected the void fraction increases with air weight fraction, but the rate of increase decreases at higher air weight fractions.

Figure 5 shows the variation of void fraction with pressure. When the pressure is increased (keeping the air weight fraction constant) there are two effects coming into the picture.

(a) The specific volume of air decreases. As water is essentially incompressible this tends to reduce the void fraction.

(b) The slip ratio decreases and this tends to increase the void fraction (Ref. Equation 2.8).

Figure 5 shows that the void fraction increases with pressure. This implies that the latter effect i.e. the reduction in slip ratio, predominates. For an air weight fraction of 1.0% the void fraction changes from 6.4% to 47.5% as the pressure increases from 3.00 psig to 12.0 psig. i.e. the void fraction increases 7.4 times when the gauge pressure increases four times. A comparison of the curves for different air weight fractions indicates that the rate of increase in void fraction with increase of pressure

reduces at higher air weight fractions.

Figure 6 shows that the slip ratio decreases with the increase of air weight fraction. At 5.00 psig the slip ratio reduces to 29% of the initial value as the air weight fraction increases 2.5 times. At higher pressures the rate of decrease of slip ratio with air weight fraction decreases.

Increasing the pressure (keeping the air weight fraction constant) drastically reduces the slip ratio. For an air weight fraction of 1.5% the slip ratio reduces to 8% of the initial value as the pressure increases four times (from 3.00 psig to 12.00 psig.) The variation of slip ratio with pressure for different air weight fractions is shown in Figure 7.

The sharp reduction of slip ratio with air weight fraction and pressure is a disadvantage from both heat transfer and moderating effect standpoints as it results in an increase in void fraction.

The distribution of voids within the cross section of the channel is shown in Figure 8. This indicates a definite tendency for the air to collect near the centre of the flow channel. This tendency was observed throughout the range of investigation, particularly at higher air weight fractions.

This type of results are necessary for the stability analysis of Boiling Water Reactors. Two types of instabilities can occur in a nuclear power reactor. They are (i) fundamental instability, when the total reactor power fluctuates without

any appreciable change in the shape of the power distribution within the core (ii) spatial instability due to differences in the power levels between the different regions of the reactor core.

The steam voids in a Boiling Water Reactor displace a part of the moderator, and the moderator density is reduced. Under most conditions the void coefficient of reactivity is negative, and this has a stabilizing effect on reactor operation. Under certain conditions, however, the void coefficient of reactivity may be positive, thus making the reactor unstable. Further, the spatial variations in moderator density caused by the presence of voids alter the shape of the neutron flux distribution and, consequently, the spatial power distribution within the core. It is, therefore, important to have precise information regarding the variation of void fraction with the various system parameters, and also the distribution of voids within the coolant channel.

Even though the void data obtained from the present investigation using air-water mixture cannot be directly used in the stability analysis of nuclear reactors, they contribute to the better understanding of the phenomenon of two-phase flow, as they throw light on the effect of pressure and mixture quality on the two important properties of flowing two-phase mixtures - the void fraction and the slip ratio.

REFERENCES

1. M.M. El-Wakil, Nuclear Power Engineering, McGraw Hill Book Company, New York, 1962.

2. H.H. Hooker & G.F. Popper, A Gamma ray attenuation method for void fraction determination in experimental boiling heat transfert test facilities, Argonne National Laboratory Report No.ANL 5766, 1958.

3. M. Petrick & B.S.Swanson, Radiation attenuation method of measuring density of a two-phase fluid, The Review of Scientific Instruments, 29, 1079, 1958.

4. H.S. Isbin, Neil C. Sher and K.C. Eddy, Void fractions in two-phase steam-water flow, A.I.Ch.E. Journal 3, 136, 1957.

5. H.S. Isbin, H.A. Rodriguez, H.C. Larson and B.D. Pattie, Void fraction measurements in two-phase flow, A.I.Ch.E. Journal, 5, 427, 1959.

6. J.F. Marchaterre and M. Petrick, The Prediction of steam volume fractions in boiling systems, Nuclear Science and Engineering, 7, 525, 1960.

7. R.A. Condon, and Neil C. Sher, Measurement of void fractions in parallel rod arrays, Nuclear Science and Engineering, 14, 327, 1962.

8. H.C. Perkins, and M. Yusuf, A void measurement technique for local boiling, Nuclear Science and Engineering, 11, 304, 1961.

9. Supplement to ASME Power Test Codes, Chapter 4, Flow Measurement, American Society of Mechanical Engineers, New York, 1959.

10. R.F. Martinelli et al, Isothermal pressure drop for two-phase two component flow in a horizontal pipe, Trans. ASME, 66, 139, 1944.

11. H.A. Johnson, and A.H. Abou-Sabe, Heat transfer and pressure drop for turbulent flow of air-water mixtures in a horizontal pipe, Trans. ASME, 74, 977, 1952.

12. D.D. Glower, Experimental reactor analysis and radiation measurements, McGraw-Hill Book Company, New York, 1965.

13. M. Price, Nuclear radiation detection, McGraw-Hill Book Company, New York, 1958.

14. R.D. Evans, The atomic nucleus, McGraw-Hill Book Company, New York, 1955.

APPENDIX

COUNTING STATISTICS AND ERROR ANALYSIS

Complete elimination of error in physical measurements is impossible. It is, therefore, essential to specify the probable error in reporting the result of any measurement.

Nuclear processes in common with all microscopic processes are random in nature. Consequently the laws of statistical distribution are applicable to experimental counting data. There are three probability distribution laws or frequency distributions which have found considerable application in the statistical analysis of radiation measurements. They are

(a) the normal distribution,

(b) the binomial distribution and

(c) the Poisson distribution.

For random processes whose probability of occurrance is small, while the number of trials becomes very large and the mean values remain fixed, the binomial distribution can be approximated by the Poisson distribution. Both Poisson and binomial distribution laws reduce in the limit to normal distribution.

Poisson law states that the probability of observing exactly n counts in a given time interval is

$$P(n) = \frac{m^n e^{-m}}{n!} \qquad \text{(A.1)}$$

where m is the true mean counts for the given time interval.

For Poisson distribution the standard deviation is given by (Ref. 12)

$$\sigma = (\bar{n})^{\frac{1}{2}} \qquad .. \qquad .. \qquad (A.2)$$

where $\bar{n}$ is the average number of counts for the given time interval.

When the number of counts is very large the Poisson distribution may be approximated by Gaussian or normal distribution equation.

When a series of N observations are made the standard deviation of the average $\bar{n}$ is given by (Ref. 12)

$$\sigma_{av} = \left(\frac{\bar{n}}{N}\right)^{\frac{1}{2}} \qquad .. \qquad .. \qquad (A.3)$$

The standard deviation is used as a precision index in the statistical error analysis and it can be calculated using the above expressions.

Standard Error

The physical significance attached to the standard deviation for normal distribution is that 68.3 percent of all observations will fall within $\pm\sigma$ of the mean. This means that a single observation will not differ from the true mean by more than $\pm\sigma$ in 683 observations out of 1000. Usually the true mean is not known. Rather, a single measurement of n counts is made. This value is reported as $n \pm n^{\frac{1}{2}}$.

Here it is assumed that

$$n \simeq \bar{n} = \sigma^2 \quad ..$$

If n is the number of counts for a period of time t the counting rate is

$$r = \frac{n}{t}$$

This value with its standard deviation may be stated as

$$r \pm \sigma_r = \frac{n}{t} \pm \frac{n^{\frac{1}{2}}}{t}$$

i.e. $$r \pm \sigma_r = r \pm \left(\frac{r}{t}\right)^{\frac{1}{2}} \quad .. \quad .. \quad (A.4)$$

Stated in terms of percentage error that is

$$r \pm \frac{100}{(rt)^{\frac{1}{2}}} \% = r \pm \frac{100}{n^{\frac{1}{2}}} \% \quad .. \quad (A.5)$$

i.e. the percentage standard error $= \frac{100}{n^{\frac{1}{2}}}$. .. (A.6)

Probable error

Another quantity frequently used in reporting to statistical error is the probable error[14]. The probable error is, by definition, exactly as likely to be exceeded as not. This error which has exactly a 50% chance of being exceeded in a normal distribution is equal to 0.6745 .

$$\therefore \text{ The probable error} = \frac{0.6745}{n}$$

$$\text{The \% probable error} = \frac{0.6745 \times 100}{n^{\frac{1}{2}}} \quad .. \quad .. \quad (A.7)$$

Table 1 gives the different percentage errors for different values of n.

TABLE 1

Total counts (n) for a given error[13]

Error Percentage	Counts	
	Standard Error	Probable Error
0.1	10^6	4.5×10^5
0.3	1.1×10^5	5.1×10^4
1.0	10^4	4.5×10^3
3.0	1.1×10^3	506
10.0	100	45

When several quantities having standard deviations σ_1, σ_2, ... σ_n are combined by either addition or subtraction the standard deviation σ_s of the result is

$$\sigma_s = (\sigma_1^2 + \sigma_2^2 + \sigma_3^2 + - - - - + \sigma_n^2)^{\frac{1}{2}} \qquad (A.8)$$

When there is a background counting rate of $r_b \pm \sigma_b$ and a total counting rate due to both source and background $\pm \sigma_t$, counting rate due to source alone is given by

$$r_s \pm \sigma_s = (r_t - r_b) \pm (\sigma_b^2 + \sigma_t^2)^{\frac{1}{2}} \qquad (A.9)$$

Sample Statistical Error Analysis

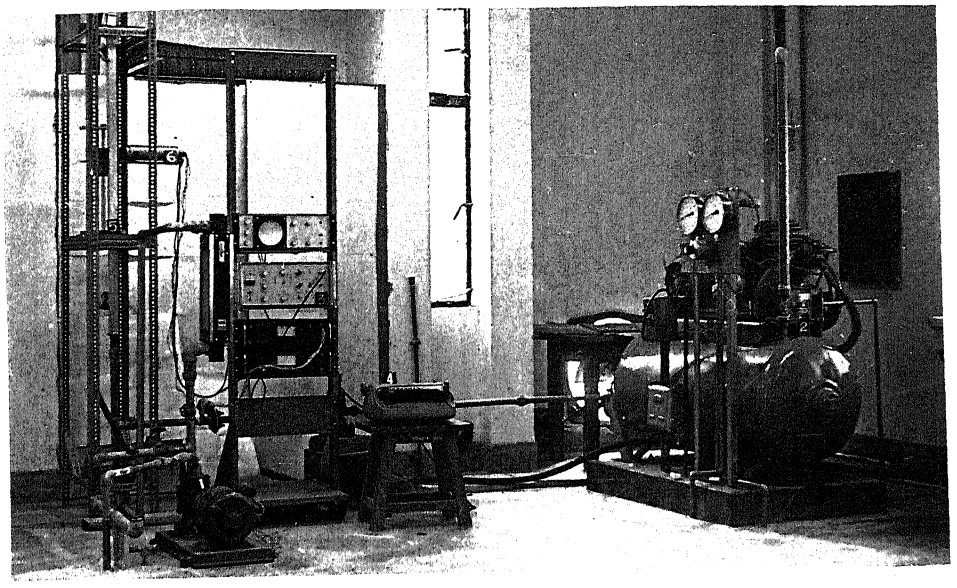
For a sample set of measured values of N_m, N_g and N_1 the statistical errors without taking into consideration the background count rate calculated using Equation A.5 and Equation A.7 are given below.

	Standard Error	Probable Error
N_m = 70501 counts/minute	0.376%	0.253%
N_g = 83896 counts/minute	0.345%	0.232%
N_1 = 47043 counts/minute	0.460%	0.310%

The maximum background count rate observed was 300 counts/minute. For the same values of N_m, N_g and N_1 the statistical errors taking into consideration the background count rate calculated using Equation A.9 are as follows:

	Standard Error	Probable Error
N_m = 70501 counts/minute	0.378%	0.255%
N_g = 83896 counts/minute	0.3465%	0.234%
N_1 = 47043 counts/minute	0.465%	0.3135%

The background count rate is very small when compared to N_m, N_g and N_1. Consequently, the differences between the statistical errors calculated with and without taking into consideration the background count rate are also extremely small.

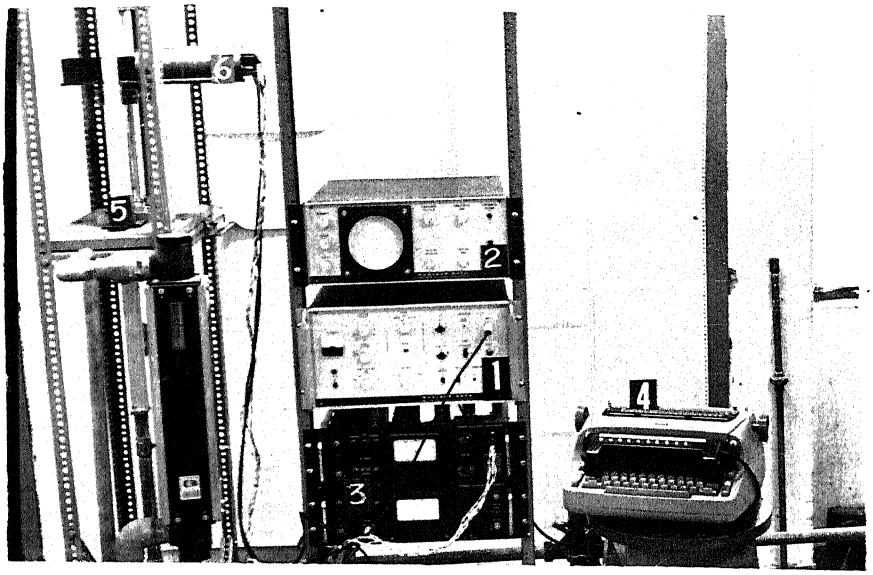


1. Water Pump 2. Air Compressor

3. Multi Channel Analyzer 4. Digital Print Out Unit

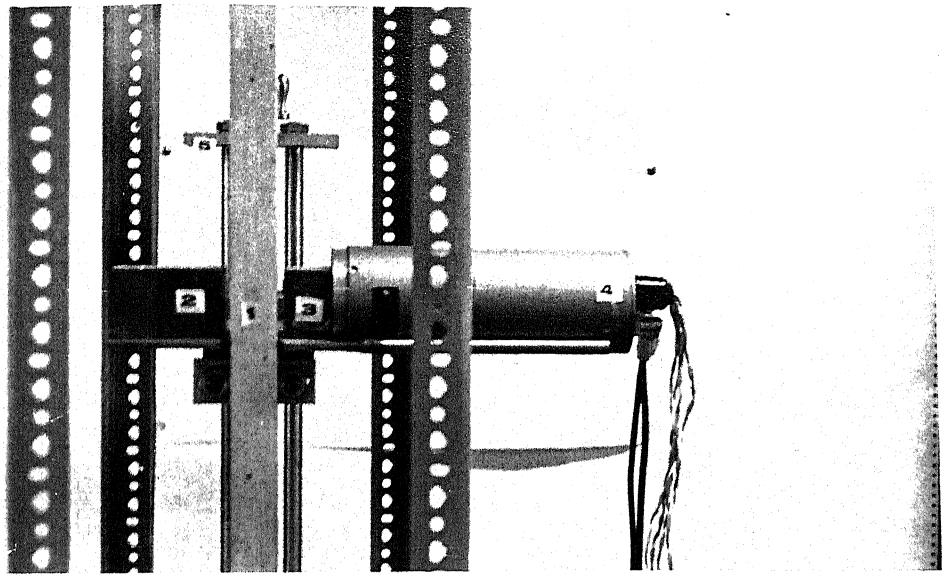
5. Flow Channel 6. Detector

FULL VIEW OF THE EXPERIMENTAL SET-UP



1. Multi Chann el Analyzer 2. Display Unit
3. Power Supply 4. Digital Print Out Unit
5. Flow Channel 6. Detector

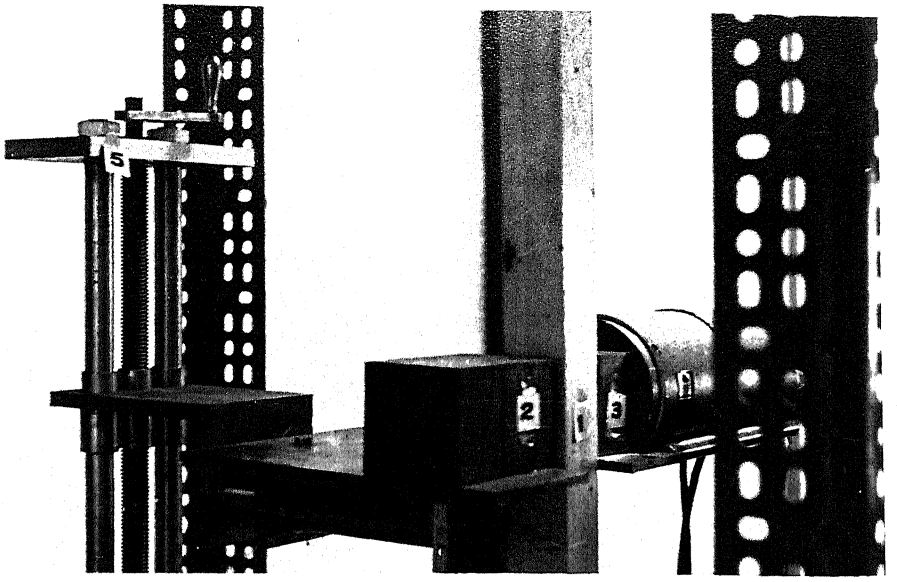
THE GAMMA RAY APPARATUS



1. Flow Channel 2,3. Collimators

4. Detector 5. Traverse Mechanism

FRONT VIEW OF THE SECTION



1. Flow Channel 2,3, Collimators

4. Detector 5. Traverse Mechanism

SIDE VIEW OF THE TEST SECTION